Risk of electrocution during fire suppression activities involving photovoltaic systems

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Riccardo Tommasini[a], Enrico Pons[a*], Federica Palamara[b], Calogero Turturici[c], Pietro Colella[a]

a Department of Electrical Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy
b Prevention and Protection Service, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy
c Ministero dell'Interno, Dipartimento dei Vigili del Fuoco del soccorso pubblico e della difesa civile, Italy
* Corresponding author: enrico.pons@polito.it

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Abstract

Firefighting activities regarding buildings normally require electric power to be disconnected before a water jet is used, in order to minimize the risk of electrocution. As for as concerns Photovoltaic Systems, during a fire event it is not possible to turn off the whole power system in order to guarantee that all the components are de-energized. The object of this paper is to estimate the safe distances to respect during firefighting involving PV Systems. To this end a series of experimental tests have been performed, in order to measure the current flowing through the water stream, under different conditions of nozzle design, jet shape, water pressure and stream length. Experimental results have been compared with data in literature. Moreover, the electrical conductivity of the water streams, which actually consists of water mixed with air, has been evaluated.

1.Introduction

Photovoltaic (PV) Systems permit electrical power to be generated by converting solar radiation into electricity. As the use of PV systems proliferates, new electrical hazards to firefighters when they are involved in the mitigation of a fire concerning photovoltaic modules, have arisen [11]. Safe firefighting activities normally require the building's electrical power to be disconnected before water is applied, to prevent risk of electrocution due to water conductivity. During a fire event, turning off the PV System in order to guarantee that all the components are de-energized is difficult. In fact, these systems are live as long as there is light. Therefore, also at night, when illuminated by artificial light sources, such as fire department light trucks or the fire itself, PV systems continue to generate electricity.

At the moment limited data about the hazards associated with the application of water to a PV array during firefighting suppression efforts are available.

The NFPA Fire Protection Handbook [1], as for as concerns firefighting regarding live electrical equipment, recommends the use of water spray streams rather than solid streams, whenever possible. The Handbook lists safe distance values between the nozzle and live electrical equipment, for various nozzle sizes, resulting from studies by several authorities, but all these studies are based on AC high voltages. Furthermore, the Handbook itself says that these safe distance values are not wholly consistent, because the results of different tests vary.

Also IEEE Standard 979-1994 [3], in the presence of energized equipment at high AC voltages, recommends the use only of spray-type nozzles at the minimum distance from the equipment of 3 m, but this Standard just considers solid streams generated by large nozzles (29-38 mm), at high pressures (5-7 bar) and high water flow rates (750-950 l/min).

Other values for the safe distance to electric lines for various high AC voltages are given in an old circular written by the State of Illinois-USA [5], which analyses the influence of different water resistivities on the evaluation of the safety distance. However, this report only considers solid streams generated by just one nozzle of 30 mm.

Three other studies were performed by [6], [8] and [12] on the risk of electric shock to fire fighters working next to electrical equipment, especially as regards the use of solid hose streams, used for large fires, near high voltages involved in electrical transmission and distribution. In particular, the influence of pressure and nozzle diameter on stream current and the safe distances to be respected were analyzed.

On the other hand, as for as concerns DC power and voltages, typical of a PV system (600-1000 V), part of the Research Project: 'Firefighter Safety and Photovoltaic Installations' performed by Underwriters Laboratories (UL) [7] is dedicated to evaluating, by experimental tests, the safe distances to be respected during firefighting involving PV Systems. The safe distance values of this study are compared with the results of the present work.

Finally, the German Research Project about fire safety regarding PV systems [13][14] ought to be mentioned; part of this project is dedicated to a series of tests with the goal of verifying the requirements from 'VDE 0132' [4] concerning the safety distances to respect during fire fighting where energized systems are concerned, in order to avoid the risk of electrocution. In particular, according to this German Standard, the distances which have to be observed, at low voltage DC (< 1,5 kV), are 1 m for a spray jet and 5 m for a full water jet, although both the jets are generated by a particular nozzle which is the multi-purpose branchpipe 'DIN 14365'.

From this literature survey, it transpires that safety distances strongly depend on the type of nozzle, on the pressure and on the water flow rate. Thus, the objective of this work is to determine the safe distances from which a water stream may be directed against PV systems during firefighting and the study focuses on the Italian contest, considering the most common types of nozzles used in Italy.

2.Materials and methods

The electric shock hazard due to application of water is dependent on voltage, distance, water pressure, mass flow rate, conductivity, geometry and dispersion of the suppression stream [1].

As for as concerns water, by nature it is not a good conductor [5], but dissolved minerals and impurities increase its conductivity and their amount vary with location (see Tab.1). To this end the resistivity of the water used in the experimental tests has been measured. By applying a voltage at the end points of a pipe full of water and by measuring the current, it has been estimated a resistivity of about 46 Ω·m.

Table 1. Typical electrical conductivity and resistivity in Italian waterworks

Town	Conductivity [µS/cm]	Resistivity [Ωm]
Aosta	400	25,0
Torino	412	24,3
Genova	283	35,3
Milano	602	16,6
Bolzano	300	33,3
Trento	600	16,7
Trieste	344	29,1
Firenze	497	20,1
Perugia	464	21,6
Ancona	525	19,0
L'Aquila	300	33,3
Roma	650	15,4
Napoli	720	13,9
Campobasso	452	22,1
Bari	377	26,5
Potenza	365	27,4
Palermo	791	12,6
Cagliari	335	29,9

The form in which water is used (pattern, droplet size and flow rate) has been also investigated. To this end it has been used the two types of nozzles most diffused in Italy:

- a branchpipe type, whose nozzle diameter is 9 mm and that can produce jets or spray patterns;
- a pistol-grip type whose nozzle is adjustable from a solid stream to a wide fog that is produced with spinning teeth.

The voltage source used in the experimental tests is a DC power supply of 250,5 V. The positive pole of the power supply is connected to the nozzle, while the negative pole to a target, constituted by a 48x48 cm^2 metal square grid, surrounded by a PVC pipe and mounted 1,5 m from ground. Fig.1 shows the target which has been used for the experimental measures.

Figure 1. Target used for experimental test

The current flowing in the circuit (see Fig. 2) has been measured using the two types of nozzle, under different water pressures (1.5, 2, 3, 4, 5, 6 bar) and different distances between the nozzle and the target (60, 90, 120, 150, 180 cm).

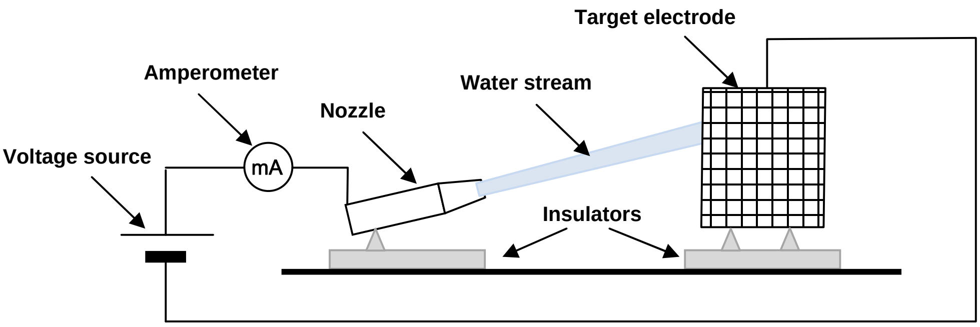

Figure 2. Experimental set-up

Firstly, in order to check the measured values, current values have been measured in two ways: both by an amperometer TEK DMM870 and by a voltmeter Mastech MY65 coupled with a shunt resistance. Percent error between the two kind of measures never exceeds 3%.

Subsequently the set of experimental measures has been obtained by the voltmeter coupled with the shunt resistance, due to the lower systematic error they provide.

3.Results

Solid stream: Determination of leakage DC currents through water jets

Tabs. 2 and 3 show the circulating current and the flow rate values depending on the different distances and pressures for the two types of nozzle (see Figs. 3 and 4).

Table 2. ‘Branchpipe’ experimental results

distance	PRESSURE											
	1,5 [bar]		2 [bar]		3 [bar]		4 [bar]		5 [bar]		6 [bar]	
[cm]	Flow rate [l/min]	Current [µA]	Flow rate [l/min]	Current [µA]	Flow rate [l/min]	Current [µA]	Flow rate [l/min]	Current [µA]	Flow rate [l/min]	Current [µA]	Flow rate [l/min]	Current [µA]
60	61	475	73	473	91	458	106	421	115	400	123	400
90	58	306	71	291	87	267	101	258	112	255	124	242
120	61	214	71	209	88	189	101	179	115	175	124	171
150	60	170	70	160	90	135	104	140	112	135	125	140
180	60	100	70	75	87	75	104	90	112	100	125	95

Figure 3. ‘Branchpipe’ experimental set-up

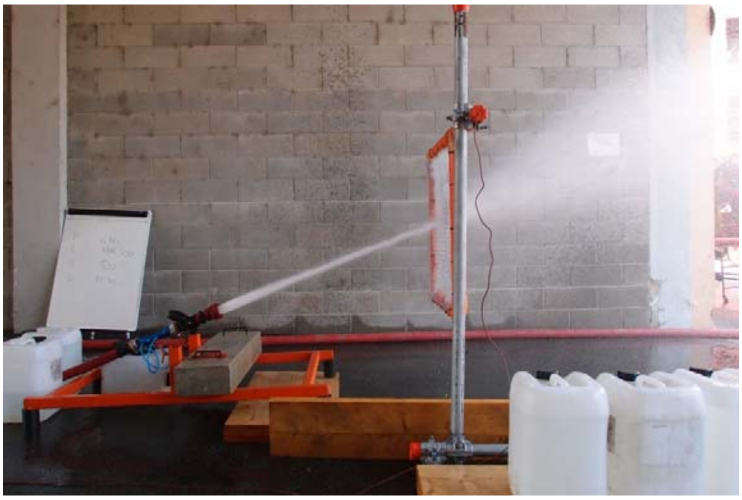

Figure 4. 'Pistol-grip' experimental set-up

Table 3. 'Pistol-grip' experimental results

distance	PRESSURE											
	1,5 [bar]		2 [bar]		3 [bar]		4 [bar]		5 [bar]		6 [bar]	
[cm]	Flow rate [l/min]	Current [μA]	Flow rate [l/min]	Current [μA]	Flow rate [l/min]	Current [μA]	Flow rate [l/min]	Current [μA]	Flow rate [l/min]	Current [μA]	Flow rate [l/min]	Current [μA]
60	190	960	230	870	280	830	320	815	380	796	400	790
90	215	755	250	693	315	650	350	650	380	625	400	600
120	205	606	240	545	310	494	340	461	380	461	400	455
150	205	480	244	446	308	404	350	378	383	376	400	355
180	200	394	240	373	310	333	345	327	380	312	400	297

As far as concerns the 'Pistol-grip' nozzle, the outlet opening is ring-shaped. Thus, an 'equivalent' diameter, of about 16 mm, has been estimated by measuring pressure and flow rate values at the nozzle (see Tab.3).

During each experimental test, under the same operating conditions, current values have been measured for about 10 seconds and the fluctuations in the readings of the measurement apparatus were negligible. For each current value measured, based on multimeter specifications, measurement uncertainties which are lower than 2% have been estimated.

Figs. 5 and 6 represent current values vs. distance at different pressures, for the 'Branchpipe' and 'Pistol-grip' nozzle type, respectively. In particular, in both figures, the two lines represent the best fits of the experimental results for 1,5 and 6 bar. The colored area inside the lines is the region where the experimental current values vary for 2, 3, 4 and 5 bar. It can be noticed that, at the nozzle exit, as the solid stream becomes stronger, i.e. the nozzle pressure increases, the value of the current decreases and thus the stream conductivity is reduced. This is due to the fact that water splitting into drops, with the consequent mix in the jet of water and air, increases with pressure [12] and the stream length at which the jet begins to break up into discrete drops, causing a rapid rise in electrical resistance, depends on the water pressure and on the nozzle design.

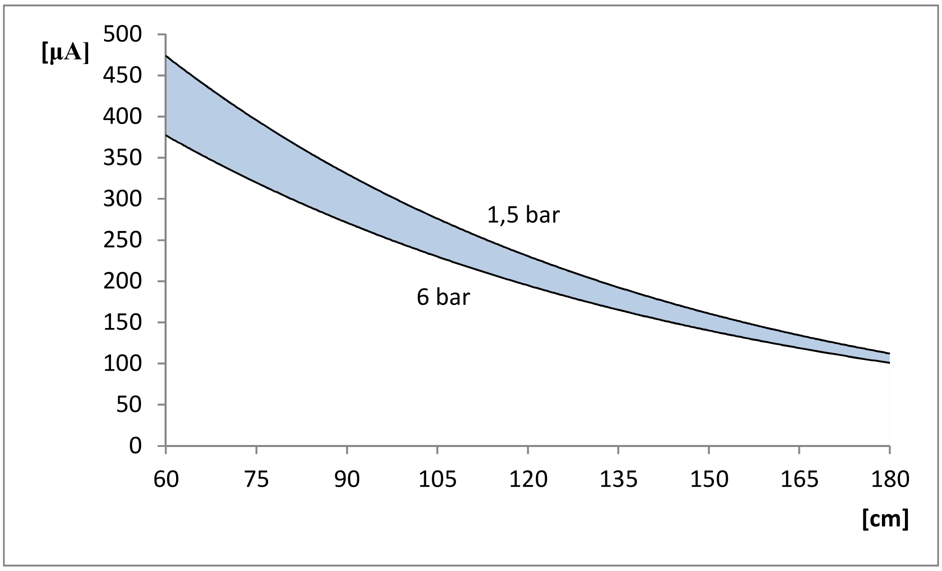

Figure 5. 'Branchpipe'- Current vs. distance

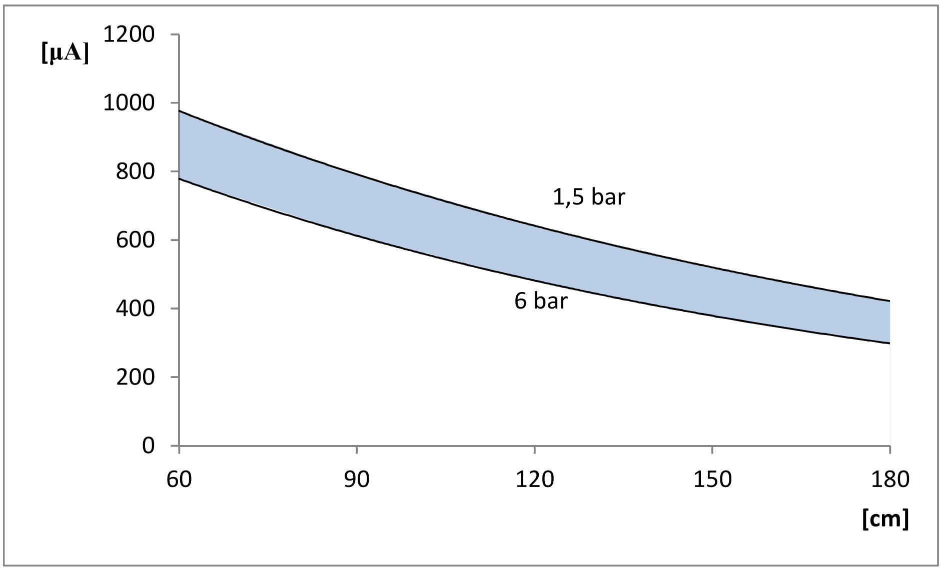

Figure 6. 'Pistol-grip' Current vs. distance

4.Discussion

4.1. Solid stream: evaluation of the electrical conductivity of the water jets

The whole shape of both experimental jets generated by the two types of nozzle can be approximated to a frustum of cone. Therefore in order to characterize the electrical conductivity of the solid streams, the water resistance of a frustum of cone full of water along the jet axis is calculated as shown in equation (1):

$$R_w(x) = \frac{\rho l}{(r_2 - r_1)\pi}\left[\frac{1}{r_1} - \frac{1}{\left(r_1 + \frac{(r_2 - r_1)}{l}x\right)}\right] \quad (1)$$

where

$R_w(x)$ is the water resistance of the jet full of water, having the shape of a frustum of cone

x is the jet axis direction

ρ is the water resistivity

r_2 and r_1 are the radii of the two basis of the frustum of cone

l is the frustum of cone height.

Then, the full jet water resistance (see equation 1) has been compared with the resistance equations 2.a and 2.b, referring to the two experimental jets. These equations have been obtained using the best fits of the resistance values vs. distance, at the pressure of 1,5 bar and resistance values have been calculated based on Ohm's law, dividing the voltage used in the experimental tests of 250,5 V by the experimental current values, illustrated in Tabs. 2 and 3.

$$R_w^{bp}(x) = 2{,}6 \cdot 10^5 e^{1{,}23 \cdot x} \quad (2.a)$$

where

$R^{bp}{}_w(x)$ is the water resistance of the 'Branchpipe' water jet x is the jet axis direction

$$R_w^{pg}(x) = 1{,}7 \cdot 10^5 e^{0{,}74 \cdot x} \qquad (2.b)$$

where

$R^{pg}{}_{w}(x)$ is the water resistance of the ‘Pistol-grip’ water jet

x is the jet axis direction.

In this way it has been possible to discover how the resistivity of a jet constituted by water mixed with air, like the ones under study, differs, along the jet axis, from that of a full jet characterized by the same shape, whose resistivity remains constant. In Figure 7 a function, called z(x) is represented for both ‘Branchpipe’ and ‘Pistol-grip’ experimental jets. For each of the two kinds of jet this function is the ratio between the resistance equation obtained experimentally (equations 2.a and 2.b) and the resistance equation of the jet if it was full of water (equation 1). z(x) has been calculated assuming a jet length of 1,8 m and by measuring r_2 and r_1 respectively at 1,8 m and at the nozzle exit. Moreover, the water resistivity value obtained experimentally (46 Ω·m) has been considered. Thus, z(x) represents the behavior of the resistivity of the jets along their axis when water splits into drops and the jets become a mix of water with air.

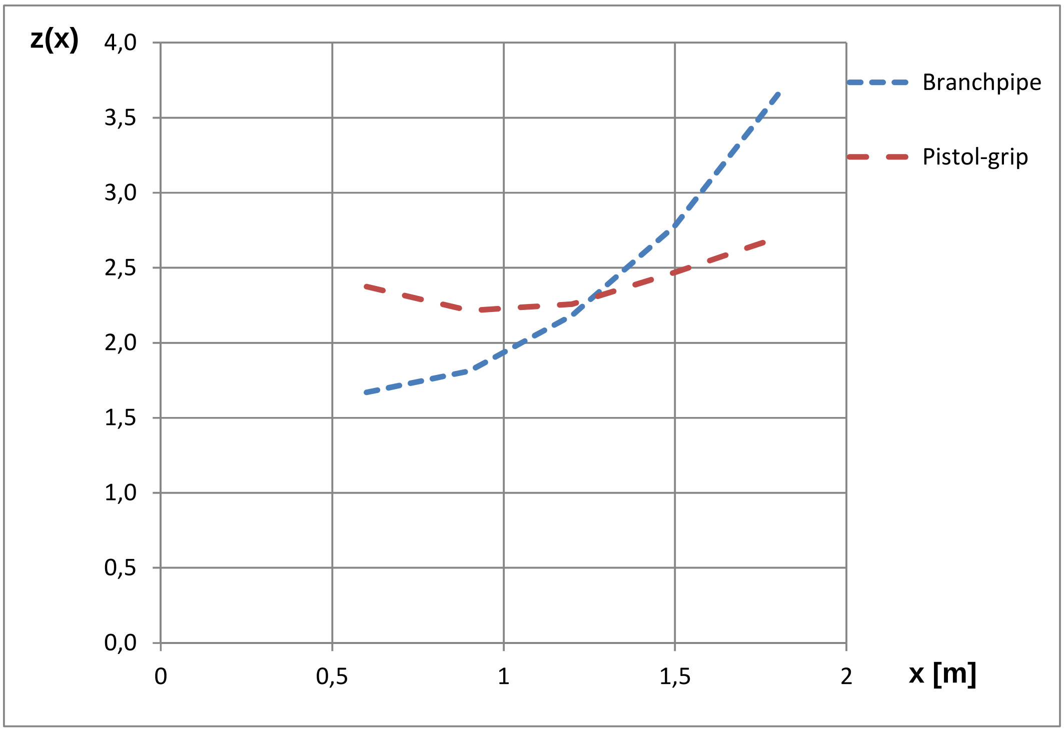

Figure 7. Resistivity behavior in ‘Branchpipe’ and ‘Pistol-grip’ jets

Similar studies were performed by [10] and [15]. In fact, in order to take into account the variability of stream resistance, [10] introduced a coefficient α which multiplies water resistance and whose value varies with stream length in a way which depends on water pressure and resistivity. Furthermore, [15] divided the water stream into three zones. In the first zone, constituted by a simply water jet, α increases relatively slowly with length. In the second zone, in which the water begins to break into drops, α increases at a very rapid rate. The third zone consists entirely of discrete drops and α becomes very large and then increases relative slowly.

Moreover, in order to study the electrical resistivity trend in the two kinds of the experimental water jets, resistance values along the jet length have been analyzed. In particular, as it is shown in equation (3), based on the current values which have been measured, resistance incremental ratio $\Delta R_i/\Delta x_i$ along the water jet length has been calculated.

$$\frac{\Delta R_i}{\Delta x_i} = \frac{R_i - R_{i-1}}{x_i - x_{i-1}} \tag{3}$$

where

x_i are the distances from the jet source at which current values have been measured

R_i are the resistance values calculated for each of the x_i distances.

Fig. 8 shows $\Delta R_i/\Delta x_i$ in function of branchpipe jet length, calculated at the different pressures. It can be seen that it is almost constant, except for the highest distance. This is due to the fact that, with this type of nozzle, water splitting into drops becomes relevant just at this distance.

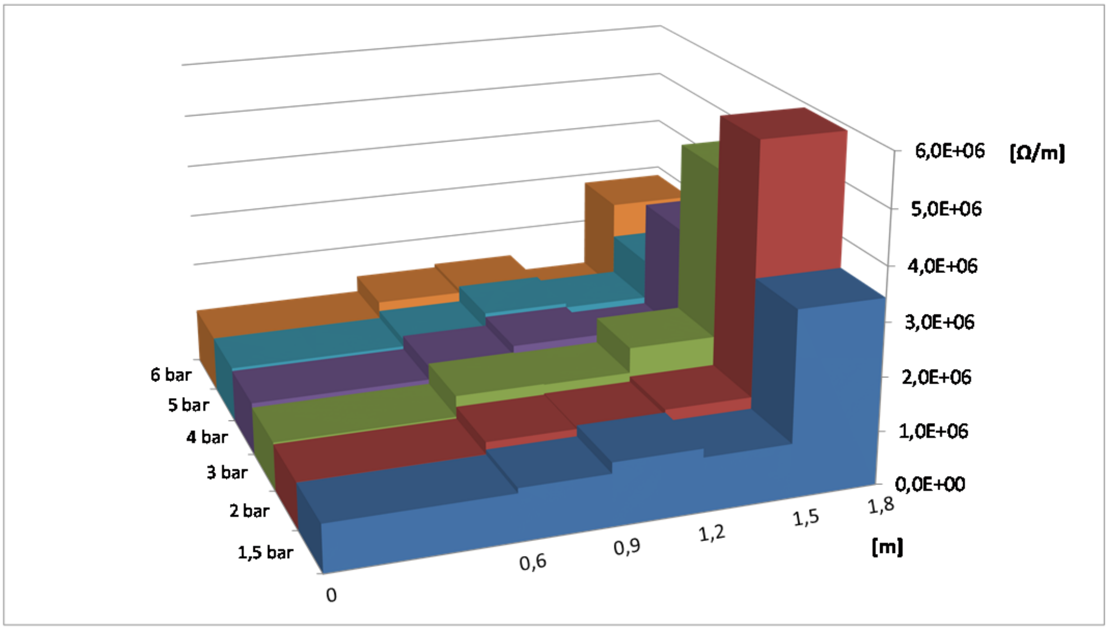

Figure 8. ‘Branchpipe’ resistance incremental ratio along water jet length

Fig.9 shows $\Delta R_i/\Delta x_i$ in function of ‘Pistol-grip’ jet length, calculated at the different pressures; this trend is completely different respect to the previous one. It can be seen that, initially, $\Delta R_i/\Delta x_i$ is not a monotonic function of jet length. This is due to the fact that, actually, as can be seen in Fig. 10, there is a jet length, depending on nozzle pressure, at which the solid jet tend to close to itself.

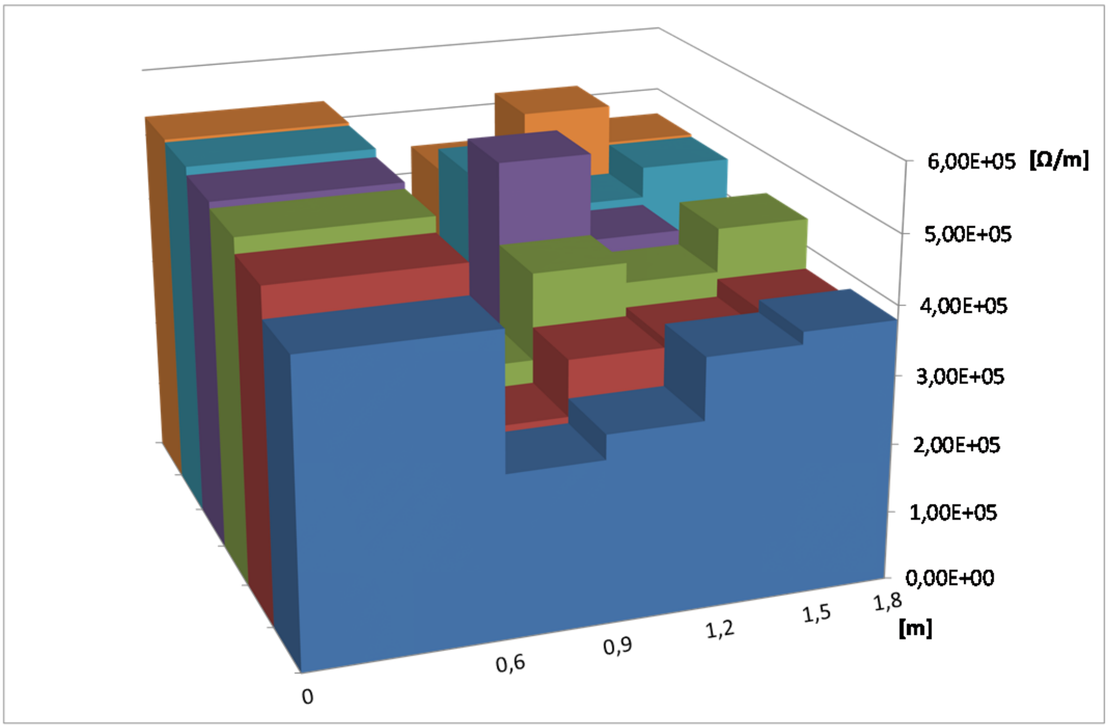

Figure 9. 'Pistol-grip' resistance incremental ratio along water jet length

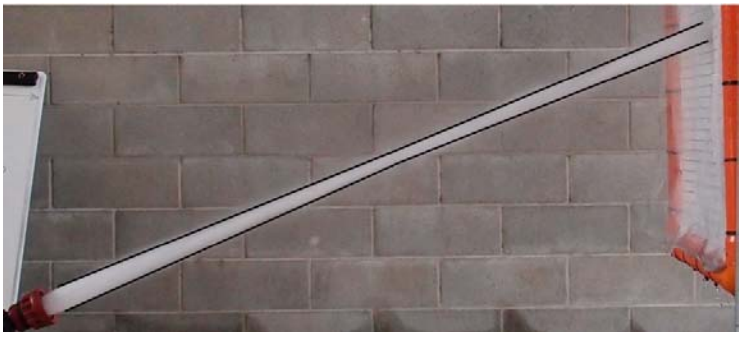
Figure 10. 'Pistol-grip' jet shape

Therefore resistance trend has different behavior inside the two jets generated by the two different nozzles, because of the different shapes of the streams along the first 2 m stream length, as it is also confirmed by [15], which studies the influence of the internal nozzle design on stream resistance.

4.2. Solid stream: Calculation of 'Safe distance'

Current flowing through the human body produces a range of physiological effects including perception, muscular contractions, tetanization and ventricular fibrillation of the heart. By literature [2], [7], it is assumed 'safe' the condition where the current through the body would be 2 mA or less, because this is the level of DC current considered to be below the threshold of perception. Actually it would be possible to refer to current values higher than 2 mA without physical damages, anyway it has been chosen to refer to 2 mA in order to be conservative.

The electric shock hazard due to application of water on PV Systems is dependent on systems voltage, water conductivity, distance and stream pattern. As concerns solid streams, in the safe distance calculation based on the experimental results, it has to be taken into account that PV systems are energized with a voltage up to 600-1000 V DC. Therefore, in order to estimate what might be a safe distance for DC power at voltages typical of a PV system, the experimental currents which flow down the stream have been scaled by a factor 4. Exponential extrapolation of branchpipe type and pistol-grip type experimental data concerning the pressure of 1,5 bar (see Fig. 11), permits to estimate respectively 0,6 m and 1,4 m as safety distances. For both the nozzles it has been considered the lower pressure, because, as it is shown in Figs. 5 and 6, it is the one that implies the higher currents. Thus, for a branchpipe type, whose nozzle diameter is about 1 cm, the minimum distance from the energized equipment is at least 0,6 m; for a pistol-grip type whose equivalent nozzle diameter is about 1,5 cm, the minimum distance from the energized equipment is at least 1,4 m. The influence of nozzle diameter on safe distance is confirmed by [12] which states that safe distance increases as the diameter of the nozzle becomes greater, because of the lowering in resistance due to the greater area of the jet cross-section.

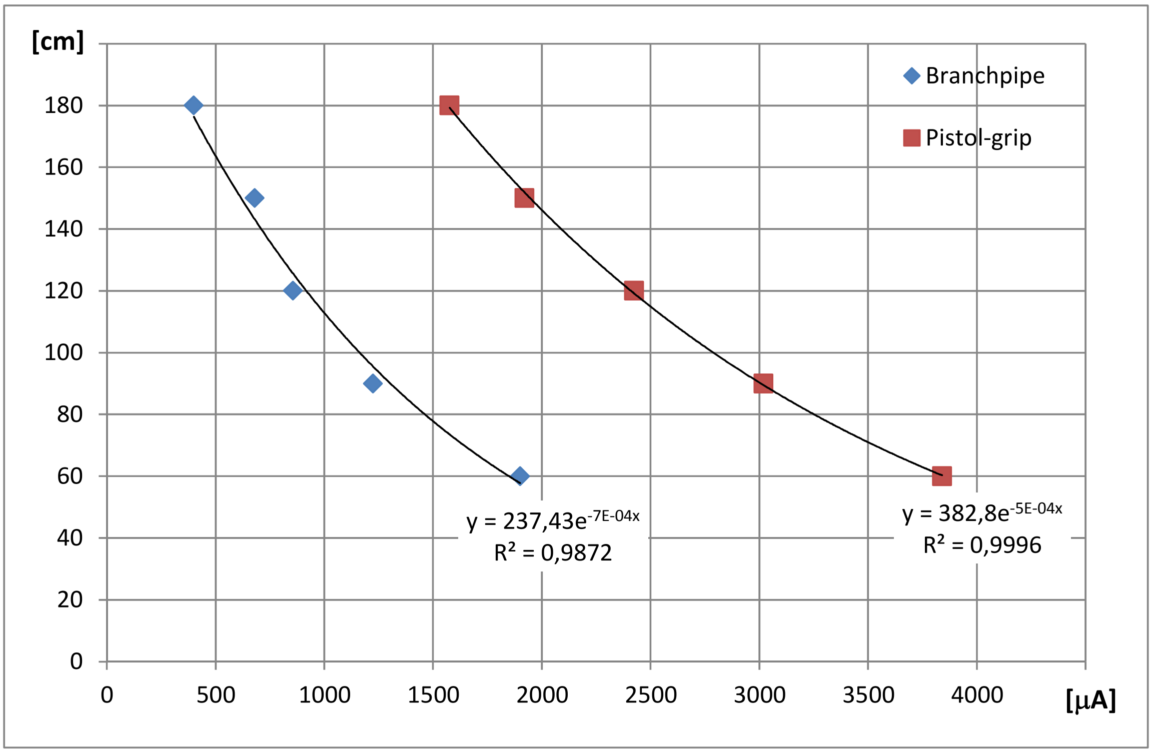

Figure 11. Branchpipe and Pistol-grip- Distance vs. current at 1000 V DC

Moreover, since salt content of water greatly affects its ability to conduct electricity, the safety of firemen also depends upon the chemical quality of the water they use. Thus, in each contest, the estimation of 'safe distance' should be done taking into account the water (pool, pond or sea) used by firemen.

The results of this study have been compared with the ones found in literature. In particular, the 'Firefighter Safety and Photovoltaic Installations Research Project' performed by Underwriters Laboratories (UL) [7] has been taken into account. A type of nozzle used in UL experiments is similar to the pistol-grip type used in our experiments. Tab. 4 shows the comparison between current values, for different voltages, when the target is at a distance of 3 m and 4,6 m from the nozzle, with a water pressure of 3 bar. In order to perform this comparison, firstly Italian experimental data have been extrapolated to higher distances by means of the formula shown in Fig. 6 concerning the pressure of 3 bar. Then the current values have been scaled by a voltage factor, because the Italian tests have been performed at 250,5 volts. Finally, current values have been scaled by a factor regarding the different water resistivity: in fact UL has used for the tests pond water whose resistivity is just 8,9 Ω·m, meanwhile water considered in this study has a resistivity of 46 Ω·m.

Table 4. Comparison between UL and Italian results

V [V]	distance[m]	UL experimental data [mA]	Scaled Italian experimental data [mA]
1000	3,05	3,4	2,3
1000	4,57	1,3	0,7
600	3,05	2,1	1,4
600	4,57	1,1	0,4
300	3,05	1,1	0,7
300	4,57	0,2	0,2
50	3,05	0,2	0,1
50	4,57	0,1	0,03

In the same conditions, UL and Italian current values have the same order of magnitude, but the UL values are higher than Italian ones. This can be due to the fact that the UL nozzle implies a flow rate higher than the Italian one (360 vs. 300 l/min). Moreover, the copper target plate used by UL is different from the Italian target (see Fig. 1). This implies different water dispersion as the jet hits the target: near the UL target plate much more water is dispersed and there is much more dripping over the ground. The current values measured are actually the sum of the current I_1 flowing through the water jet and the current I_2 flowing through the dripping water and the ground (see Fig. 12); the second component may be higher in UL experiments, because more water is dispersed and drips near the UL target plate.

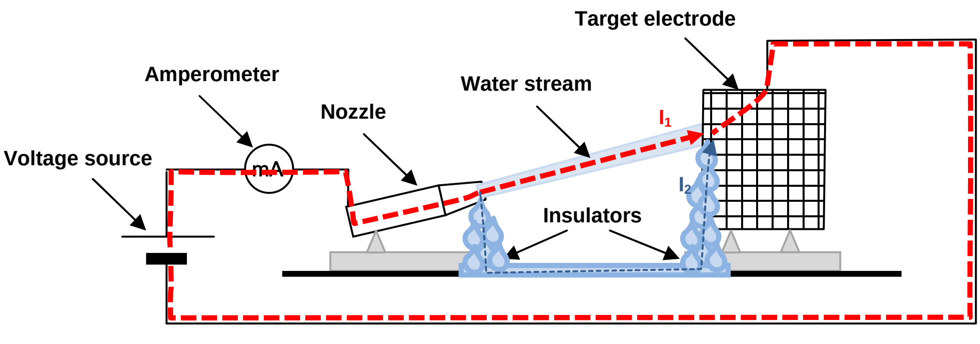

Figure 12. Components of the measured current

As far as 'Branchpipe' experimental results, it is possible to compare them with the ones found out with similar experiments by [8]. During the experiments described in this paper, a voltage of 460 V has been applied and the water has a resistivity of 32 Ω·m. Thus, by scaling the current values by the voltage factor (460 V vs. 1000 V) and by the resistivity factor (32 Ω·m vs. 46 Ω·m), it is possible to see that, at the same stream length, 'Branchpipe' current values exceed the literature ones by less than 10%. The discrepancy is probably due to the fact that in the literature the diameter nozzle is slightly less (7 mm) than the Branchpipe one (9 mm).

4.3. ‘Spray stream’ and ‘Wide fog’

The nozzle of the ‘branchpipe’ has also been adjusted to a 25° spray stream, at the pressure of 4 bar (see Fig.13). In this case, for 250,5 V DC, negligible values of current (less than 0,04 mA) have been measured. This is due to the fact that the electrical resistance of the stream increases when the water is broken up into small droplets and the air spaces between the drops of water in the stream limit electrical conductance. This is confirmed by a series of experimental tests performed in order to evaluate the break-up length of liquid jets in an air blast atomizer [9]. This technique is based on the measure of electrical conductivity along the length of the jet, by applying a potential between the nozzle and a probe and by moving the probe along the jet axis. Low voltages indicate low resistance between the nozzle and the probe and therefore continuity of the liquid jet, while high voltages indicate high resistance between the probe and the nozzle and therefore marginal or no continuity of the liquid jet. In these experimental test, initially voltage values increase gradually downstream the spray nozzle, then the slope begins to increase rapidly, because this is the location of the break up point.

Figure 13. ‘Branchpipe’ hose – Spray stream

Moreover, in order to measure current flow in the presence of a wide fog, the experimental set up, shown in Fig. 14 has been set.

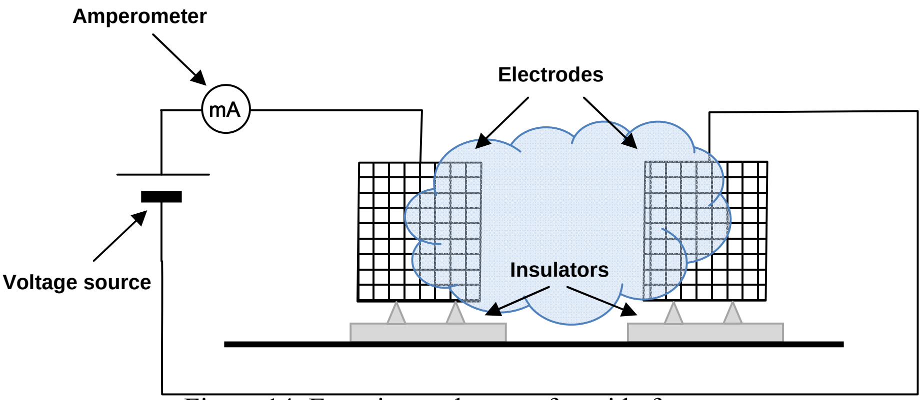

Figure 14. Experimental set-up for wide fog measurements

In this case, as it is shown in Fig. 15, two targets have been used and the two electrodes have been connected to them. The targets have been positioned in a dedicated container in which fog is generated.

Figure 15. Targets used for wide fog measurements

Tab. 5 shows the fog properties .

Table 5. Fog properties

Distance from the source [mm]	Drops diameter [µm]	Drops mean velocity [m/s]
10	3,4 - 19,0	14,4 - 33,0
50	7,1 - 29,8	0,8 - 14,0

Current values between the two electrodes have been measured by varying the distance between the targets. Negligible values of current have been measured even at low distances (1 meter).

Wide fog and spray stream results agree with the ones by UL study [7]; in fact in UL report they say that 'As the nozzle is adjusted down from the full stream towards fog, the leakage current quickly drops to near zero'.

5.Conclusion

This paper has dealt with firefighting conditions in which a fire cannot be extinguished by non-conducting agents and in which equipment which cannot be de-energized, like PV systems, is involved. In particular, as far as the water jets used to extinguish fires, the experimental tests described here demonstrate that these kinds of jet can be used safely on voltages as high as 1000 V DC, by respecting safety distances. These distances have been estimated by considering the lowest nozzle pressure data, for the sake of precaution; in fact, the stronger is the stream, the more it breaks into discontinuous filaments and droplets and the higher is the jet resistivity. This experimentation has been performed by considering the most common types of nozzles used in Italy, because safety distances strongly depend on the type and the diameter of the nozzle and on water conductivity.

This study regards PV systems on roofs which involve firefighting operations at low pressures (less than 10 bar). The case of photovoltaic panels positioned in fields, in which firefighting requires water at high pressures is still under study.

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